BIBLIOGRAPHY ON SEMICONDUCTORS FOR THERMOELECTRIC USE

By E. H. Illsley and H. Kato

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BIBLIOGRAPHY ON SEMICONDUCTORS FOR THERMOELECTRIC USE[1]

by

E. H. Illsley[2] and H. Kato[3]

INTRODUCTION

This bibliography is the first report of a Bureau of Mines research project on thermoelectric materials. Interest in such research has increased because of recent success in the design of commercial products, including generators and refrigerators, using the principles of thermoelectricity. This success is made possible by the discovery of semiconductors that have much higher efficiencies than the metals and alloys formerly studied.

Thermoelectricity is a term that includes a large number of phenomena relating heat to electrical energy. However, the most important applications arise from two effects discovered by Seebeck in 1822 and by Peltier in 1834. When pieces of two unlike materials are joined at their two ends to form a continuous circuit, both of these effects may be observed. If the two junctions are maintained at different temperatures, an electromotive force known as the Seebeck voltage is generated. If, on the other hand, a current is made to flow through the circuit, the junctions of the materials will be found to differ in temperature. This phenomenon is called the Peltier effect.

The application of the Seebeck effect to electric power generation is not now competitive with steam or gasoline generators. However, the use of semiconductor thermoelements has already given better than an order-of-magnitude improvement in efficiency over metallic thermopiles. Refrigerators or constant-temperature baths based on the Peltier effect have become practicable with the use of similar semiconductor materials. Peltier refrigerators and thermoelectric generators share the advantages of silent operation, flexibility in size, and absence of moving parts.

The reason for preparing this bibliography is that much of the work published on the subject is difficult for the American researcher to locate. Although the Russians have pioneered both in experimental and theoretical

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investigations of thermoelectric effects, their journals do not have wide circulation in this country. Even within the United States, communication is hindered because most of the research is being done at industrial laboratories where publications are scanty.

The bibliographic references are annotated to increase their usefulness, and they are arranged alphabetically in five sections, each containing articles on similar subjects. Most of the references appeared in the period between 1950 and the summer of 1958. When possible, the abstracts have been made from the original article. The references were selected from Chemical Abstracts, Science Abstracts, and other current journals. Important articles may have been missed, because pertinent abstracts in the journals are arranged under a variety of headings. The bibliography does not include articles dealing with research on vacuum thermoelectric devices, solar batteries, or metallic thermocouples.

Useful bibliographies on thermoelectricity also are found in the following references: Goldsmid, H. J. (Peltier cooling research, abs. 14), Ioffe, A. F. (Russian work to 1957, abs. 7), Johnson, V. A. (theoretical articles to 1954, abs. 8), McCollum, P. A. (patents from 1887 and experiments with metallic thermocouples, abs. 88), and Meissner, W. (comprehensive bibliography including work to 1935, abs. 9).

The assistance of the librarians of the Albany (Oreg.) station of the Bureau of Mines and the Science Division of the University of Oregon Library is gratefully acknowledged.

Preparation of this bibliography was suggested by Dr. Earl T. Hayes, chief metallurgist, Bureau of Mines, Washington, D. C.

LIST OF SOURCES WITH ABBREVIATIONS

Abhandl. braunschweig. wiss. Ges.	Abhandlungen der braunschweigischen wissenschaften Gesellschaft
Acta Cryst.	Acta Crystallographica
Advances in Physics	Advances in Physics
Am. Jour. Sci.	American Journal of Science
Am. Mineral.	American Mineralogist
Ann. Physik	Annalen der Physik
Appl. Sci. Research	Applied Scientific Research
Bell System Tech. Jour.	Bell System Technical Journal
British Jour. Appl. Phys.	British Journal of Applied Physics
Bull. Am. Phys. Soc.	Bulletin, American Physical Society
Canadian Jour. Phys.	Canadian Journal of Physics
Compt. rend.	Comptes rendus hebdomadaires des séances de l'académie des sciences
Doklady Akad. Nauk S. S. S. R.	Doklady Akademii Nauk S. S. S. R.
Doklady Akad. Nauk S. S. S. R., Fiz. Khim.	Doklady Akademii Nauk S. S. S. R., Fizicheskaya Khimiya
Elec. Eng.	Electrical Engineering
Helv. Phys. Acta	Helvetica Physica Acta

Izvest. Akad. Nauk S. S. S. R., Ser. Fiz.	Izvestiya Akademii Nauk S. S. S. R., Seriya Fizicheskaya
Izvest. Akad. Nauk S. S. S. R., Otdel. Tekh. Nauk	Izvestiya Akademii Nauk S. S. S. R., Otdelenie Tekhnicheskikh Nauk
Jour. Am. Ceram. Soc.	Journal, American Ceramic Society
Jour. Appl. Phys.	Journal of Applied Physics
Jour. Chem. Phys.	Journal of Chemical Physics
Jour. Electrochem. Soc.	Journal, Electrochemical Society
Jour. Electronics	Journal of Electronics
Jour. Electronics and Control	Journal of Electronics and Control
Jour. Phys. Chem. Solids	Journal, Physics and Chemistry of Solids
Jour. phys. radium	Journal de physique et le radium
Jour. Phys. U. S. S. R.	Journal of Physics (U. S. S. R.)
Jour. Phys. Soc. (Japan)	Journal, Physical Society of Japan
Kältetechnik	Kältetechnik
Nature	Nature
Phil. Mag.	Philosophical Magazine
Phil. Trans. Roy. Soc. London	Philosophical Transactions of the Royal Society of London
Physica	Physica
Phys. Rev.	Physical Review
Phys. Ztschr.	Physikalische Zeitschrift
Proc. Cambridge Phil. Soc. (England)	Proceedings, Cambridge Philosophical Society (England)
Proc. Phys. Soc.	Proceedings, Physical Society
Proc. Roy. Soc. (London)	Proceedings, Royal Society of London
Research	Research
Rev. Modern Phys.	Reviews of Modern Physics
Rev. Sci. Instr.	Review of Scientific Instruments
Sci. Am.	Scientific American
Sov. Phys. Doklady	Soviet Physics Doklady
Sov. Phys. Tech. Phys.	Soviet Physics Technical Physics
Trans. AIME	Transactions, American Institute of Mining and Metallurgical Engineers
Jspekhi Fiz. Nauk	Uspekhi Fizicheskikh Nauk
VADC	Wright Air Development Center
Zhur. Tekh. Fiz.	Zhurnal Tekhnikii Fiziki
Ztschr. angew. Phys.	Zeitschrift für angewandte Physik
Ztschr. anorg. Chem.	Zeitschrift für anorganische Chemie
Ztschr. anorg. u. allgem. Chem.	Zeitschrift für anorganische und allgemeine Chemie
Ztschr. Naturforsch.	Zeitschrift für Naturforschung
Ztschr. Physik	Zeitschrift für Physik

LITERATURE REFERENCES[4]

General References in the Field

1. GOLDSMID, H. J. Use of Semi-Conductors in Thermoelectric Generators. Research, vol. 8, 1955, pp. 172-177.

This general survey gives the problems and advantages of thermoelectric generation.

2. IOFFE, A. F. [Physics of Semiconductors.] (Russian.) Akad. Nauk Publishing House, Moscow, 1957, trans. Infosearch, London, 1958.

3. ___. Revival of Thermoelectricity. Sci. Am., vol. 199, No. 5, 1958, pp. 31-37.

This popular article is concerned with the advantages and problems of thermoelectric generation and cooling.

4. ___. Poluprovodnikovye Termoelementy [Semiconductor Thermoelements]. (Russian.) Akad. Nauk Publishing House, Moscow, 1956, 103 pp.

This book contains a summary of the theoretical and experimental results obtained for thermoelectric generators as of 1956.

5. ___. [Thermoelectric and Thermal Properties of Semiconductors.] (French.) Jour. phys. radium, vol. 18, 1957, pp. 209-213.

The efficiency of a thermocouple depends on the ratio of electrical to thermal conductivity. Impurities scatter phonons; mean free path decreases as resistivity increases. Uni- and bi-polar diffusion was discussed, with examples taken from data on PbSe, Bi_2Te_3, and PbTe.

6. IOFFE, A. F., STIL'BANS, L. S., IORDANISHVILI, E. K., AND STAVITSKAYA, T. S. Termoelektricheskoe Okhlazhdenie [Thermoelectric Cooling]. (Russian.) Akad. Nauk Publishing House, Moscow, 1956, 110 pp.

This book contains a summary of the theoretical and experimental results obtained for thermoelectric cooling by 1956.

7. ___. [Semiconductor Thermoelements and Thermoelectric Cooling.] (trans. abs. 5 and 7, by A. Gelbtuch), Infosearch, London, 1957, 184 pp.

The English edition contains some additional information on more recent Russian developments.

IORDANISHVILI, E. K. See abs. 6, 7.

8. JOHNSON, V. A. Theory of the Seebeck Effect in Semiconductors. Chap. in Progress in Semiconductors, vol. 1, Wiley & Sons, Inc., New York, N. Y., 1957, pp. 63-97.

This review article considers the electron and phonon contributions to thermoelectric power in the regions of impurity, transition, and intrinsic conductivity. It contains an excellent bibliography.

9. MEISSNER, W., AND REDDEMANN, H. Thermoelektrizität, Peltier-Effekt,

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[4] Titles enclosed in brackets are translations from the language in which the item was published.

Thomson-Effekt. [Thermoelectricity, Peltier Effect, Thomson Effect]. Handbuch der Experimentalphysik, vol. 11, part 2, Akademische Verlags G. m. b. H., Leipzig, 1935, pp. 395-544.

A detailed survey was given of the experimental methods used and results obtained in the study of thermal electromotive force, the Peltier coefficient, the Thomson coefficient, and miscellaneous other effects. Includes extensive bibliography.

REDDEMANN, H. See abs. 9.

STAVITSKAYA, T. S. See abs. 6, 7.

STIL'BANS, L. S. See abs. 6, 7.

10. TELKES, M. Efficiency of Thermoelectric Generators. Jour. Appl. Phys., vol. 18, 1947, pp. 1116-1127.

An expression was derived for the efficiency of thermoelectric generators, and several materials were discussed with reference to their suitability for use as thermoelements.

11. WILSON, A. H. Theory of Metals, 2d ed., University Press, Cambridge, 1953, 265 pp.

A basic text for the theory of metals and semiconductors; the formalism described for metals is often borrowed or extended for theoretical treatment of semiconductor problems.

Peltier Effect

12. ALTENKIRCH, E. Elektrothermische Kälteerzeugung und reversible elektrische Heizung [Thermoelectric Refrigeration and Reversible Electric Heating]. (German.) Phys. Ztschr., vol. 12, 1911, pp. 920-924.

An elementary theory of thermoelectric cooling was derived from thermodynamic considerations, assuming the Wiedemann-Franz relationship to hold.

BARANSKII, P. I. See abs. 23.

BENSON, K. E. See abs. 21.

DOUGLAS, R. W. See abs. 116.

13. GEHLHOFF, P. O., JUSTI, E., AND KOHLER, M. [Improved Theory of Thermoelectric Refrigeration.] (German.) Abhandl. braunschweig. wiss. Ges., vol. 2, 1950, pp. 149-164.

The simple theory of Altenkirch (see abs. 12) has been refined to include noncylindrical forms. The effect of contact resistance at the cold junction was discussed. It was concluded that thermoelectric refrigeration should be possible with modern materials.

14. GOLDSMID, H. J. Thermoelectric Applications of Semiconductors. Jour. Electronics, vol. 1, No. 2, 1955, pp. 218-222.

The figure of merit F' (defined as the square root of Ioffe's "Z"), is approximately proportional to the square root of the effective mass and the ratio of carrier mobility to thermal conductivity. Experiments were reported on thermoelectric refrigeration.

___. See also abs. 116.

GROOT, S. R. DE. See abs. 15.

15. HOLTAN, H., JR., MAZUR, P., AND GROOT, S. R. DE. On the Theory of Thermocouples and Thermocells. Physica, vol. 19, 1953, pp. 1109-1118.

A general expression for the thermopotential was derived from the theory of irreversible processes and applied to thermocouples and thermocells.

16. IOFFE, A. F. [Two New Applications of the Peltier Effect.] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 2, 1956, pp. 478-482; trans. Sov. Phys. Tech. Phys., vol. 1, 1956, pp. 462-465.

The heat of crystallization of metals or semiconductors was removed by Peltier cooling. It can be used to grow better crystals. Alternating current passing through a semiconducting plate generates Peltier thermal oscillations and, hence, mechanical deformation.

IORDANISHVILI, E. K. See abs. 24.

17. IORDANISHVILI, E. K., AND STIL'BANS, L. S. [Thermoelectric Microrefrigerators.] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 2, 1956, pp. 482-483.

Cooling of 75°-80° C. from 70° C. was the best single-element unloaded temperature difference obtained. A two-stage refrigerator cooled a 1-liter volume by 56° C. from 40° C. A volume of 600 cc. was held at 45° C., while the exterior temperature was varied from -21° to 70° C.

18. IORDANISHVILI, E. K., AND TKALICH, L. G. [Semiconducting Thermostat for Oscillator Circuits.] (Russian.) Zhur. Tekh. Fiz., vol. 27, No. 6, 1957, pp. 1215-1220.

Several semiconductor junctions in series were used to maintain a temperature of 20° C. in a thermally insulated volume of 100 cc. with external temperatures ranging from -60° to +60° C.

19. JUSTI, E. Elektrothermische Kühlung [Thermoelectric Cooling]. (German.) Kältetechnik, vol. 6, 1953, pp. 150-157.

The text of a lecture on thermoelectric cooling, including remarks on its theory and experiments performed by Justi's group at Braunschweig.

___. See also abs. 13.

KOHLER, M. See abs. 13.

LANDECKER, K. See abs. 20.

MAZUR, P. See abs. 15.

20. O'BRIEN, B. J., WALLACE, C. S., AND LANDECKER, K. Cascading of Peltier Couples for Thermoelectric Cooling. Jour. Appl. Phys., vol. 27, No. 7, July 1956, pp. 820-823.

Experiments were undertaken to show that increased cooling could be achieved by constructing a refrigerator with thermoelements in cascade.

21. PFANN, W. G., BENSON, K. E., AND WERNICK, J. H. Some Aspects of Peltier Heating at Liquid-Solid Interfaces in Germanium. Jour. Electronics, vol. 2, No. 6, 1957, pp. 597-610.

Peltier heating or cooling may be used in growing single crystals, producing n-p-n and n-p-n-p junctions, and zone melting. An interesting result is the Peltier coefficient for the solid against the liquid.

22. SHILLIDAY, P. F. Performance of Composite Peltier Junctions of Bismuth Telluride. Jour. Appl. Phys., vol. 28, 1957, pp. 1035-1042.

A temperature difference of 49° C. was achieved with a Peltier refrigerator, using thermoelements of n- and p-type Bi_2Te_3.

23. SHTENBEK, M., AND BARANSKII, P. I. [Methods for Precision Measurement of the Peltier Effect and the Thermoelectric Power.] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 7, 1956, pp. 1373-1388; trans. in Sov. Phys. Tech. Phys., vol. 1, No. 7, 1957, pp. 1345-1359.

Methods were developed for measuring the Peltier effect to a precision of 1 percent and measuring the thermoelectric power. For single crystals of germanium, the equation $P = \alpha T$ is not obeyed exactly.

STAVITSKAYA, T. S. See abs. 24.

STIL'BANS, L. S. See abs. 17.

24. STIL'BANS, L. S., IORDANISHVILI, E. K., AND STAVITSKAYA, T. S. [Thermoelectric Refrigeration.] (Russian.) Izvest. Akad. Nauk S. S. S. R., Ser. Fiz., vol. 20, No. 1, 1956, pp. 81-88.

The theory of Peltier refrigeration was summarized for semiconductors and illustrated for experiments with PbTe. A practical model with a volume of 10 liters was held at 4° C. in a room at 27° C.

TKALICH, L. G. See abs. 18.

WALLACE, C. S. See abs. 20.

WERNICK, J. H. See abs. 21.

25. WHITE W. C. Some Experiments With Peltier Effect. Elec. Eng., vol. 70, 1951, pp. 589-591.

Experiments were reported using Bi-Sb and Bi-Sn alloys to obtain a cooling effect of 10° C.

26. WRIGHT, D. A. Paper in Report of the Garmisch Conference in 1956: to be published in Halbleiter Problema, IV, ed. by W. Schottky.

Properties of n- and p-type Bi_2Te_3 were described, and a maximum Peltier cooling of 65° C. was obtained at a mean temperature of 17° C.

Thermoelectric and Thermal Conductivity Theory and Related Topics

27. AIRAPETIANTS, S. V. [Thermal Electromotive Force and Impurity Thermal Conductivity of a Statistical Mixture.] (Russian.) Zhur. Tekh. Fiz., vol. 27, No. 3, 1957, pp. 478-483.

A statistical analysis was made of the thermal electromotive force resulting from mixtures of pressed alloy powders.

___. See also abs. 46.

28. APPEL, J. [Thermal Electromotive Force of Nonpolar Semiconducturs.] (German.) Ztschr. Naturforsch., vol. 12A, 1957, pp. 410-424.

For nondegenerate isotropic semiconductors, the electron and lattice-wave distribution functions were solved simultaneously and self-consistently. The resulting thermoelectric power and thermal conductivity are in good agreement with measurements on germanium.

29. BEER, A. C., CHASE, M. N., AND CHOQUARD, P. F. Extension of McDougall-Stoner Tables of the Fermi-Dirac Functions. Helv. Phys. Acta, vol. 28, 1955, pp. 529-542.

Values were tabulated of F_k (η) for k = 5/2, 7/2, and 11/2, ~~and~~ η =

-4(0.1)20. The results are accurate to five significant figures.

BILLIG, E. See abs. 61.

30. **BUSCH, G., AND SCHNEIDER, M.** Heat Conduction in Semiconductors. Physica, vol. 20, 1954, pp. 1084-1086.

Measurements of the thermal conductivity of Mg_2Sn and InSb showed that the values for the electronic component of the heat conduction are about 100 times larger than expected from the Wiedemann-Franz law.

CHASE, M. N. See abs. 29.

CHOQUARD, P. F. See abs. 29.

31. **CONWELL, E. M., AND WEISSKOPF, V. F.** Theory of Impurity Scattering in Semiconductors. Phys. Rev., vol. 77, 1950, 388-390.

Lattice scattering cannot alone explain the temperature dependence of the resistivity of semiconductors. The contribution to the resistivity by scattering from ionized impurity centers was calculated, using the Rutherford scattering formula. The resulting resistivity increases with decreasing temperature.

32. **DOMENICALI, C. A.** Irreversible Thermodynamics of Thermoelectricity. Rev. Modern Phys., vol. 26, No. 2, 1954, pp. 237-275.

The thermodynamics of thermoelectric effects was presented carefully and clearly, with detailed discussion of the physical consequences. The relationships were given between the ideas and notation of this paper and those of Kelvin, Bridgman, Ehrenfest and Rutgers, Kohler, Meixner, and Meissner. References to their work are contained in the bibliography.

DRABBLE, J. R. See abs. 112.

33. **DRABBLE, J. R., AND WOLFE, R.** Anisotropic Galvanomagnetic Effects in Semiconductors. Proc. Phys. Soc., vol. 69B, 1956, pp. 1101-1108.

Anisotropic galvanomagnetic effects result from the assumption that the surfaces of constant energy are ellipsoids centered at energy extrema at equivalent points in k space. The theory is applied to the crystal class of $Bi_2Te_3:\bar{3}n$.

34. **EHRENBERG, W.** Electrical Conductivity of Simple Semiconductors. Proc. Phys. Soc., vol. 63A, 1950, pp. 75-76.

An approximate expression was obtained for the electrical conductivity of semiconductors as a function of temperature under the assumptions that the electron mean free path is determined solely by accoustical modes of lattice scattering, that only one kind of impurity center supplies the electron gas, and that conduction is in one band only.

35. **FRÖLICH, H., AND KITTEL, C.** Remark on the Paper by Prof. G. Busch. Physica, vol. 20, 1954, p. 1086.

A qualitative explanation of the results of Busch and Schneider (see abs. 30) was presented in terms of the transported ionization energy of the charge carriers.

36. **GOLDSMID, H. J.** On the Thermal and Electrical Conductivity of Semiconductors. Proc. Phys. Soc., vol. 67B, 1954, pp. 360-363; corrigendum, p. 599.

The ratio of electron mobility to thermal conductivity was predicted to be proportional to the mean atomic weight of semiconductors. The agreement with experimental observation is remarkable.

37. GOODMAN, C. H. L. Prediction of Semiconducting Properties in Inorganic Compounds. Jour. Phys. Chem. Solids, to be pub. in 1958.

___. See also abs. 112.

38. GUREVICH, L. [Thermoelectric Properties of Conductors.] Jour. Phys. U.S.S.R., part 1, vol. 9, 1945, pp. 477-488; part 2, vol. 10, 1946, pp. 67-80.

The lattice vibrations in a metal under a temperature gradient tend to scatter the electrons preferentially toward the colder end of the sample. This phenomenon is known as "phonon drag" and should create an additional term in the expression for thermoelectric power, which is inversely proportional to the temperature at high temperatures and proportional to the cube of the temperature at low temperatures.

HAAR, D. TER See abs. 56.

39. HAAR, D. TER, AND NEAVES, A. On Thermal Conductivity and Thermoelectric Power of Semiconductors. Advances in Physics, vol. 5, April 1956, pp. 241-269.

The lattice components of thermoelectric power and thermal conductivity were investigated for extrinsic semiconductors, taking into account various scattering mechanisms. Basic assumptions were discussed.

40. ___. On the Thermo-Electric Power of Metals. Proc. Roy. Soc. (London), vol. 228A, 1955, pp. 568-574.

An expression was derived for the contribution to the thermoelectric power by the lattice current at temperatures where electron-phonon scattering predominates. The sign of this contribution is opposite to that found from the simple electron theory of metals.

41. HERRING, C. Role of Low-Energy Phonons in Thermal Conduction. Phys. Rev., vol. 95, 1954, pp. 954-965.

Phonon-phonon collisions in which one phonon is of very low frequency were studied in relation to the Seebeck effect.

42. ___. Transport Properties of a Many-Valley Semiconductor. Bell System Tech. Jour., vol. 34, No. 2, March 1955, pp. 237-290.

Using Maxwellian statistics, a theory for several quantities including the thermoelectric power was developed on the basis of a "many-valley" model.

43. ___. Theory of the Thermoelectric Power of Semiconductors. Phys. Rev., vol. 96, No. 5, 1954, pp. 1163-1187.

Gives a detailed treatment of the theory of the contribution to the thermoelectric power by the drag on the charge carriers exerted by phonons streaming from hot to cold.

44. IOFFE, A. F. [Estimation of the Heat Conductivity of Semiconductors.] (Russian.) Doklady Akad. Nauk S. S. S. R., vol. 87, 1952, pp. 369-372.

Heat conductivity is the sum of lattice conductivity K_1 and electronic conductivity $\underline{K_2}$, and $\overline{\underline{K_2}} = \underline{A}\sigma$; $\underline{A}$ =

1 x 10^{-6} (at 290° K.) for a nondegenerate and 1.65 x 10^{-6} for a degenerate carrier system. The boundary between these is near 2.5 x 10^{19} carriers per cubic centimeter. $\underline{K}_1$ was predicted by a phenomenological argument to increase with decreasing atomic weight and increasing hardness.

45. IOFFE, A. F. Heat Transfer in Semiconductors. Canadian Jour. Phys., vol. 34, 1956, pp. 1342-1353.

The observed thermal conductivities deviate from theoretical expectations. It was proposed that the additional heat conducted is carried partly by excitons.

___. See also abs. 47, 48, 49.

46. IOFFE, A. F., AIRAPETIANTS, S. V., IOFFE, A. V., KOLOMOETS, N. V., AND STIL'BANS, L. S. [On Increasing the Efficiency of Semiconductor Thermocouples.] (Russian.) Doklady Akad. Nauk S. S. S. R., vol. 106, No. 6, 1956, p. 98; trans. Sov. Phys. Doklady, vol. 1, No. 1, 1956; Brutcher Trans. 4075.

One may increase the ratio of carrier mobility to the lattice portion of thermal conductivity by making a solid solution with a substance of nearly the same lattice parameters. This material is included in the book by Ioffe and others on semiconductor thermoelements (see abs. 7).

IOFFE, A. V. See abs. 46.

47. IOFFE, A. V., AND IOFFE, A. F. [Influence of Additions on Thermal Conductivity of Semiconductors.] (Russian.) Doklady Akad. Nauk S. S. S. R., vol. 98, 1954, pp. 757-759.

Discusses the influence of impurity-scattering centers on phonon heat conduction.

48. ___. [Correlation of the Thermal Conductivity of a Semiconductor and the Electron Mobility.] (Russian.) Zhur. Tekh. Fiz., vol. 24, 1954, pp. 1910-1911.

The ratio of phonon to electron mean free paths was calculated for C, Si, Ge, PbS, and Te.

49. ___. [Thermal Conductivity of Semiconductors.] (Russian.) Izvest. Akad. Nauk S. S. S. R., Ser. Fiz., vol. 20, 1956, pp. 65-75.

The electronic component of thermal conductivity may be neglected for semiconductors with electrical conductivity less than 100 mhos. This paper discusses electron-phonon interaction and factors that affect phonon conductivity.

JOHNSON, V. A. See abs. 9.

KITTEL, C. See abs. 35.

KOLOMOETS, N. V. See abs. 46.

50. KONTOROVA, T. A. [On the Limits of the Practical Applicability of Pisarenko's Formula.] (Russian.) Zhur. Tekh. Fiz., part 1, vol. 24, 1954, pp. 1291-1297; part 2, vol. 24, 1954, pp. 1687-1696.

Part 1: Pisarenko's formula is valid to 15 percent in some degenerate systems where the classical distribution cannot be applied, such as atomic bond lattices to carrier concentrations of 4 x 10^{19} cm^{-3} and ionic lattices to 10^{20} cm^{-3}.

Part 2: With classical statistics, the thermoelectric power is shown to be proportional to the reduced Fermi level and increases at low temperatures. For degenerate semiconductors, the thermoelectric power is linear with absolute temperature.

KORENBLIT, L. L. See abs. 62.

51. LAUTZ, G. Zur Theorie der differentiellen Thermokraft von Halbleitern [On the Theory of the Differential Thermoelectric Power of Semiconductors]. (German.) Ztschr. Naturforsch., vol. 8A, 1953, pp. 361-371.

Formulas were derived for the thermoelectric power of semiconductors, using the classical model and various approximations for the Fermi energy.

52. MacDONALD, D. K. C. Thermo-Electric Power in Semi-Conductors. Physica, vol. 20, 1954, pp. 996-998.

An analysis was made from momentum considerations of the electron-phonon interaction, causing electrons to be swept along by phonons. Qualitative agreement was obtained with experiment; further experiments were suggested.

53. MADELUNG, VON O. Zur Theorie der Leitfähigkeit in isotropen Halbleitern [On the Theory of Conductivity in Isotropic Semiconductors]. (German.) Ztschr. Naturforsch., vol. 9A, 1954, pp. 667-674.

Conductivity phenomena in isotropic semiconductors are treated extensively, both for isothermal and adiabatic conditions and for the commonly encountered scattering mechanisms. Fermi integrals in tabular form are included.

54. MAKINSON, R. E. B. Thermal Conductivity of Metals. Proc. Cambridge Phil. Soc. (England), vol. 34, 1938, pp. 474-497.

A comparison of the observed Lorentz ratio ($\kappa e/\sigma T$), with the theoretical values shows that, for monovalent metals, the lattice thermal conductivity is unimportant at any temperature, whereas in bismuth (taken as an example of a metal with 10^{-2} conduction electrons per atom), it plays a major role at low temperatures. The phonons were assumed to be in thermal equilibrium.

55. McDOUGALL, J., AND STONER, E. C. Computation of Fermi-Dirac Functions. Phil. Trans. Roy. Soc. London, vol. 237A, 1939, pp. 67-104.

Series expansions and numerical integration methods for $\underline{F}_{\frac{1}{2}}(\eta)$ are discussed. Tables were presented for $\frac{2}{3}\underline{F}_{\frac{3}{2}}(\eta)$, $\underline{F}_{\frac{1}{2}}(\eta)$, $w\underline{F}'_{\frac{1}{2}}(\eta)$, $w^2\underline{F}''_{\frac{1}{2}}(\eta)$, and $w^3\underline{F}'''_{\frac{1}{2}}(\eta)$ to six decimal places for $-4.0 \leq \eta \leq +4.0$ and to five decimal places for $4.0 \leq \eta \leq 20.0$.

NEAVES, A. See abs. 39, 40.

56. NEAVES, A., AND HAAR, D. TER Thermal Conductivity of Semiconductors. Phys. Rev., vol. 95, 1954, p. 596.

Using a Maxwell distribution for the conduction electrons, the electron and lattice thermal conductivities have been evaluated by the methods of Wilson and Makinson.

57. PAPET, R. M. Remarks on "Efficiency of Thermoelectric Generators". Jour. Appl. Phys., vol. 19, 1948, p. 1180.

A commentary on the paper by Telkes (see abs. 10). The maximum output of a thermoelectric generator obtains for equal external and internal resistances, but the maximum efficiency occurs when $(\underline{R_1}/\underline{R_g})^2 = 1 + \underline{T_h}F^2$, using notation of Goldsmid (see abs. 1), where F^2 equals Ioffe's $\underline{z}$, and $\underline{R_1}$ and $\underline{R_g}$ are the load and generator resistances, respectively.

58. PARROTT, J. E. Some Contributions to the Theory of Electrical Conductivity, Thermal Conductivity, and Thermoelectric Power in Semiconductors. Proc. Phys. Soc., vol. 70B, 1957, pp. 590-607.

First, a phenomenological theory was presented, assuming the Kelvin relations. Then, maintaining the symmetry of the electron-phonon interactions, the electrical and thermal conductivities and thermoelectric coefficients were calculated from the Boltzmann equation.

___. See also abs. 61.

59. PLYAT, SH. N. [Problem of Extending Odelevski's Generalized Theory of Conduction to Thermal Conductivity.] (Russian.) Zhur. Tekh. Fiz., vol. 27, No. 12, 1957, pp. 2789-2790.

Formulas were presented for the thermal conductivity of porous substances and compared with experimental results on corundum.

60. PRICE, P. J. Ambipolar Thermodiffusion of Electrons and Holes in Semiconductors. Phil. Mag., vol. 46, 1955, pp. 1252-1260.

A calculation was made of the contribution of the ambipolar diffusion of electrons and holes down a temperature gradient to the electronic component of the thermal conductivity and to the Nernst effect.

61. ROSE, F. W. G., BILLIG, E., AND PARROTT, J. E. Simple Derivation of the Thermoelectric Voltage in a Non-Degenerate Semiconductor. Jour. Electronics and Control, vol. 3, No. 5, 1957, pp. 481-486.

The assumptions made in this derivation include: Uniform carrier concentration, small temperature gradients, spherical energy surfaces, and negligible impurity scattering.

62. SAMOILOVICH, A. G., AND KORENBLIT, L. L. [Contemporary State of the Theory of Thermoelectric and Thermomagnetic Phenomena in Semiconductors.] (Russian.) Uspekhi Fiz. Nauk, vol. 49, 1953, part 1, pp. 243-272; part 2, pp. 337-383.

Part 1. This review is based on the thermodynamics of irreversible processes. Onsager's principle was used to establish the applicability of the Kelvin relations to semiconductors. Formulas were given for calculating thermoelectric power.

Part 2. Kinetic theory - This review is based on the "single-electron" theory of conduction. (50 refs.)

SCHNEIDER, M. See abs. 30.

STIL'BANS, L. S. See abs. 46.

STONER, E. C. See abs. 55.

63. STRATTON, R. On the Elementary Theory of Thermoelectric Phenomena. British Jour. Appl. Phys., vol. 8, 1957, pp. 315-321.

The theory of thermoelectric phenomena was calculated in detail to bring

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out the physical significance of the various parameters.

64. **TAUC, J.** Theory of the Thermal e.m.f. of Semiconductors. Czech. Jour. Phys., vol. 3, No. 4, 1953, pp. 282-303.

The theory of thermal electromotive force was extended to nonhomogeneous semiconductors. A discussion was included of the influence of potential barriers, nonequilibrium electron concentrations or velocity, and the influence of high-temperature gradients.

65. **TAUTS, YA.** [Thermoelectric Phenomena in Semiconductors With Non-Uniform Charge Carrier Concentration.] (Russian.) Izvest. Akad. Nauk S. S. S. R., Ser. Fiz., vol. 20, 1956, pp. 1479-1483.

Nonuniform charge distributions may be obtained by the use of point contacts in thermoelectric measurements, by illumination, or by a combination of these two effects.

WEISSKOPF, V. F. See abs. 31.

66. **WILSON, A. H.** Theory of Electronic Semiconductors. Proc. Roy. Soc. (London), part 1, vol. 133A, 1931, pp. 458-491; part 2, vol. 134A, 1932, pp. 277-287.

Part 1: The quantum theory of conduction leads naturally to a division of crystals into conductors and insulators, and various properties of insulators are worked out. It is the first detailed treatment of energy-band theory.

Part 2: The effect of impurity atoms was considered in providing extra electron states in the forbidden band of the lattice.

WOLFE, R. See abs. 32.

67. **WRIGHT, R. W.** Effect of the Mean Free Path of Electrons on the Electrical Properties of Non-Metals. Proc. Phys. Soc., vol. 64A, 1951, pp. 984-999.

Electrical coefficients were calculated on the basis of the Lorentz-Sommerfeld theory, using various mean free path theories.

Experimental Methods, Materials, and Applications

68. **AUSTIN, I. G., GOODMAN, C. H. L., AND PENGELLY, A. F.** New Semi-Conductors With the Chalcopyrite Structure. Jour. Electrochem. Soc., vol. 103, No. 11, 1956, pp. 609-610.

The compounds $CuInS_2$, $AgInSe_2$, $CuInSe_2$, $AgInTe_2$, $CuInTe_2$, and $CuFeS_2$ were prepared and their optical energy gaps measured. Several ingots showed considerable cracking.

BENSON, K. E. See abs. 102.

69. **BETTS, A. L., AND McCOLLUM, P. A.** Unconventional Electrical Power Sources. WADC TR-54-409, part 1, 1954, sec. I, pp. 11-17, sec. IV, pp. 2-6.

Efficiency considerations were discussed for thermocouple generators.

BOGOVAROVA, N. N. See abs. 71.

70. **BOLTAKS, B. I., AND TARNOVSKII, N. N.** [Electrical Properties of Chalcopyrite. Effect of Surface Treatment on the Rectifying Properties of the Crystals.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 402-409.

The resistivity and thermal electromotive force were determined for several natural and synthetic samples of chalcopyrite from 20° to 600° C.

The rectifying nature of the contact with tungsten was studied as a function of etching treatment.

CHASMAR, R. P. See abs. 99.

71. CHIZHIKOV, D. M., GULYANITSKAYA, Z. F., AND BOGOVAROVA, N. N. [Electrical and Heat Conductivities of Copper and Nickel Sulfide Systems.] (Russian.) Izvest. Akad. Nauk S. S. S. R., Otdel. Tekh. Nauk, No. 6, 1955, pp. 109-113.

Copper-nickel sulfides and copper-nickel-iron sulfide alloys were prepared. Their phase compositions were studied by hardness and microstructure determinations and their electrical and thermal conductivities determined.

COBLE, R. L. See abs. 87.

DANIELSON, G. C. See abs. 95.

DOMENICALI, C. A. See abs. 93.

DOUGLAS, R. W. See abs. 77.

FRANCL, J. See abs. 87.

FRANK, G. See abs. 81.

72. FREDERIKSE, H. P. R. Thermoelectric Power of Germanium Below Room Temperature. Phys. Rev., vol. 92, 1953, pp. 248-252.

Below about 200° K., the thermoelectric power of germanium increases considerably above the predicted value and obtains a maximum at 15° K. The mechanism suggested for this is phonon disequilibrium.

73. GAFNER, G. Application of a Transient Method to the Measurement of the Thermal Conductivity of Rocks and Building Materials. British Jour. Appl. Phys., vol. 8, 1957, pp. 393-399.

Apparatuses for small and large rock samples were described with accuracies to 7 and 5 percent, respectively.

74. GEBALLE, T. H., AND HULL, G. W. Seebeck Effect in Germanium. Phys. Rev., vol. 94, 1954, pp. 1134-1140.

The Seebeck effect in germanium below 250° K. shows an increase with decreasing temperature, which was ascribed to an interaction between the electron and phonon systems.

75. ___. Seebeck Effect in Silicon. Phys. Rev., vol. 98, 1955, pp. 940-947.

The increase in the Seebeck voltage in silicon below 200° K. was ascribed to electron-phonon interaction.

76. GLAZOV, V. M., MIRGALOVSKAYA, M. S., AND PETRAKOVA, L. A. [New Semiconductors With Chalcopyrite Structure.] (Russian.) Izvest. Akad. Nauk S. S. S. R., Otdel. Tekh. Nauk, No. 10, 1957, pp. 68-70.

Twelve compounds of the ABX_2 type, where A was Cu, Ag; B was Al, Ga, Sn; and X was Se, Te, were synthesized, and their X-ray spectra and conductivity as a function of temperature were studied.

GOODMAN, C. H. L. See abs. 68.

77. GOODMAN, C. H. L., AND DOUGLAS, R. W. New Semi-Conducting Compounds of Diamond Type Structure. Physica, vol. 20, 1954, pp. 1107-1109.

This paper suggests ternary compounds related to $CuFeS_2$ and quaternary compounds related to stannite: Cu_2FeSnS_4.

78. GOTTSTEIN, G. Über die Gültigkeit der thermodynamischen Beziehungen für Peltierwarme und Thomsonwärme, und über die galvano- und thermo-magnetischen Effekte bei variablen Leitern [Concerning the Validity of the Thermodynamic Relations for Peltier and Thomson Heat, and Concerning the Galvano- and Thermo-Magnetic Effects for Different Conductors]. (German.) Ann. Physik, series 4, vol. 43, 1914, pp. 1079-1100.

The author checked the Kelvin relations experimentally. The relation $e = \frac{\pi}{T}$ was verified, and $\frac{de}{dT} = \frac{\sigma_2 - \sigma_1}{T}$ was not quantitatively proved.

79. GRANVILLE, J. W., AND HOGARTH, C. A. Study of Thermoelectric Effects at the Surfaces of Transistor Materials. Proc. Phys. Soc., vol. 64B, 1951, pp. 488-494.

An exploration with a whisker contact of specimens of Ge and PbS showed that the polarity of the thermoelectric effect is characteristic of the bulk material only for uncontaminated cleaved or etched surfaces.

GULYANITSKAYA, Z. F. See abs. 71.

80. GUSEVA, L. N., AND OBECHKIN, B. I. [Thermoelectric Power of Silicon-Chromium.] (Russian.) Doklady Akad. Nauk S. S. S. R., vol. 112, No. 4, 1957, pp. 681-683.

The thermoelectric power and electrical conductivity were measured as a function of composition and, at the composition $CrSi_2$, as a function of temperature. At $CrSi_2$, $\sigma = 150$ mhos and $\alpha = 90\mu V/deg$.

81. HAHN, H., FRANK, G., KLINGER, W., MEYER, A. D., AND STÖRGER, G. [Investigations of Ternary Chalcogenides. V. Ternary Chalcogenides With Chalcopyrite Structures.] (German.) Ztschr. anorg. u. allgem. Chem., vol. 271, 1953, pp. 153-170.

Twenty compounds were found that can be represented by ABX_2 where A is Cu or Ag; B is Al, Ga, Sn, or Tl; and X is S, Se, or Te. Tl compounds are not as stable as the other ones. They were mostly prepared by solid-state reactions from pressed pellets.

HEIKES, R. R. See abs. 85.

82. HENISCH, H. K. Thermoelectric Measurements on Semiconductors. Proc. Phys. Soc., vol. 64B, 1951, p. 1014.

The sign of the Seebeck coefficient may be used to determine the sign of the charge carrier when: (1) The substance is not intrinsically conducting at the temperature of the experiment, (2) the surface is not contaminated, and (3) the substance does not contain a nonuniform distribution of impurity centers.

HOGARTH, C. A. See abs. 79.

HULL, G. W. See abs. 74, 75.

IOFFE, A. F. See abs. 83, 84.

83. IOFFE, A. V., AND IOFFE, A. F. [Simple Method of Measuring Thermal Conductivity.] (Russian.) Zhur. Tekh. Fiz., vol. 22, No. 12, 1952, pp. 2005-2013.

The substance to be measured was first clamped between two copper blocks at room temperature. Then the lower block was immersed in a low-temperature bath and the time variation of the temperatures of the two blocks observed. Accuracy to 3-5 percent is claimed for measurements taking about 5 minutes; the method is applicable between 10^{-3} and 10^{-1} cal./cm./sec./°C.

84. IOFFE, A. V., AND IOFFE, A. F. [Certain Regularities in the Values of the Thermal Conductivities of Semiconductors.] (Russian.) Doklady Akad. Nauk S. S. S. R., vol. 97, 1954, pp. 821-822.

The thermal conductivity of atomic and ionic crystals was studied. In ionic crystals the thermal conductivity decreases with increasing atomic weight and with increasing $\frac{A_1}{A_2}$, where A_1 and A_2 are the atomic weights of the components.

85. JOHNSTON, W. D., HEIKES, R. R., AND SESTRICH, D. Preparation, Crystallography, and Magnetic Properties of the $Li_xCo_{1-x}O$ system. Jour. Phys. Chem. Solids; to be published in 1958.

KASHTANOVA, A. M. See abs. 96.

86. KELEN, A., AND SVEDBERG, P. Thermoelectric Transistor, a Possible Batteryless Amplifying Semiconductor Device. Appl. Sci. Research, vol. 6B, 1957, pp. 369-378.

The conditions were discussed that are necessary for power amplification by a semiconductor containing a temperature gradient.

87. KINGERY, W. D., FRANCL, J., COBLE, R. L., AND VASILOS, T. Thermal Conductivity: X. Data for Several Pure Oxide Materials Corrected to Zero Porosity. Jour. Am. Ceram. Soc., vol. 37, No. 2, part 2, 1954, pp. 107-110.

Data were presented for the experimental values of thermal conductivity for several oxide ceramics as a function of temperature. The data were corrected for the effects of porosity.

KLINGER, W. See abs. 81.

88. McCOLLUM, P. A. Unconventional Electrical Power Sources. WADC TR-54-409; part 2, 1955, pp. 17-26, 56-64.

This report contains a description of a thermopile made of copper and constantan wire. Efficiency problems have been studied. The 79-item bibliography contains 35 U. S. patents from 1887 to 1947.

89. ___. Unconventional Electrical Power Sources, WADC TR-54-409, part 3, 1956, pp. 37-64, 88-92.

Copper-constantan and iron-constantan thermocouples were constructed and tested, and a discussion of the possibilities of thin-film thermocouples was included. The bibliography contains work on miscellaneous related subjects and emphasizes experimental work.

90. ___. Unconventional Electrical Power Sources, WADC TR-54-409, part 4, 1957, pp. 1-24.

Iron-constantan radial sheet and concentric junction thermopiles were constructed and evaluated.

___. See also abs. 69.

MEYER, A. D. See abs. 81.

91. MIDDLETON, A. E., AND SCANLON, W. W. Measurement of the Thermoelectric Power of Germanium at

Temperatures Above 78° K. Phys. Rev., vol. 92, 1953, pp. 219-226.

An experimental investigation was made of the thermoelectric power of germanium samples between 78° and 925° K.

MIRGALOVSKAYA, M. S. See abs. 76.

92. MOOSER, E., AND WOODS, S. B. Thermoelectric Power of Germanium at Low Temperatures. Phys. Rev., vol. 97, 1955, pp. 1721-1722.

The samples used were purer than those used by Frederikse (Phys. Rev. vol. 91, 1953, p. 491) and Geballe and Hull (see abs. 74). For p-type germanium, a peak of 10 mv./deg. was obtained at about 12° K.; and for n-type germanium, a peak of 6 mv./deg. at 40° K., decreasing to 0.5 mv./deg. at about 22° K.

OBECHKIN, B. I. See abs. 80.

93. PARRAVANO, G., AND DOMENICALI, C. A. Thermoelectric Behavior of Solid Particulate Systems. Nickel Oxide. Jour. Chem. Phys., vol. 26, 1957, pp. 359-366.

Measurements of thermoelectric power can be related to stoichiometric deviations on the surface of specimens.

PENGELLY, A. E. See abs. 68.

PETRAKOVA, L. A. See abs. 76.

SCANLON, W. W. See abs. 91.

94. SCHLITT, H. [Thermoelectric Vacuum Gage.] (German.) Ztschr. angew. Phys., vol. 8, No. 5, 1956, pp. 216-217.

The cold junction was on the glass tube of the gage, and the hot junction was within a heating coil. An electromotive force of 12 mv. was obtained at 10^{-2} mm. Hg, compared with 1 mv. at atmospheric pressure.

SESTRICH, D. See abs. 85.

95. SIDLES, P. H., AND DANIELSON, G. C. Thermal Diffusivity of Metals at High Temperatures. Jour. Appl. Phys., vol. 25, January 1954, pp. 58-67.

A sinusoidally varying heat source at the end of the specimen rod supplied a heat pulse detected by two thermocouples whose output was amplified and displayed on a recording system. This method may be used to determine thermal conductivity without the usual troublesome radiation error.

96. SKANAVI, G. I., AND KASHTANOVA, A. M. [Methods of Measuring the Coefficient of Thermal Electromotive Force in Semiconductors.] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 4, 1956, pp. 895-899.

The difficulties of measuring thermoelectric power were discussed, and two apparatuses were described for use up to 240° and 320° C.

97. STEELE, M. C. Magnetic Field Dependence of the Seebeck Effect in Germanium. Phys. Rev., vol. 107, 1957, pp. 81-83.

The Seebeck coefficient of n-type germanium single crystals increases with increasing field at 78°, 199°, 238°, and 278° K.

STÖRGER, G. See abs. 81.

98. STUCKES, A. D. Thermal Conductivity of Indium Antimonide. Phys. Rev., vol. 107, 1957, pp. 427-428.

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The thermal conductivity of InSb was measured as a function of temperature and purity, and the lattice thermal conductivity was deduced.

99. STUCKES, A. D., AND CHASMAR, R. P. Measurement of the Thermal Conductivity of Semiconductors. Paper in Meeting on Semiconductors, Phys. Soc. London, April 1956, pp. 119-124.

An apparatus was described in which the heat flow through the specimen also passes through two standards. Measurements may be made as a function of temperature by placing the apparatus in a vacuum furnace.

SVEDBERG, P. See abs. 86.

TARNOVSKII, N. N. See abs. 70.

100. TELKES, M. Solar Thermoelectric Generators. Jour. Appl. Phys., vol. 25, No. 6, 1954, pp. 765-777.

General considerations for solar thermoelectric generators were presented, and experimental results for different thermoelement materials and designs were discussed.

101. ___. Thermoelectric Power and Electrical Resistivity of Minerals. Am. Mineral., vol. 35, 1950, pp. 536-555.

The thermoelectric power between 10° and 100° C. and the resistivity were studied of about 75 minerals, many with several specimens from different localities.

VASILOS, T. See abs. 87.

102. WERNICK, J. H., AND BENSON, K. E. New Semiconducting Ternary Compounds. Jour. Phys. Chem. Solids, vol. 3, No. 9, 1957, pp. 157-159.

The naturally occurring compounds Cu_3AsS_4 (enargite), Cu_3SbS_4 (famatinite), Cu_3SbS_3 (tetrahedrite), Cu_3AsS_3 (tennantite), $CuSbS_2$ (wolfsbergite), and Ag_3AsS_3 (proustite), as well as the new compounds, Cu_3SbSe_4, $CuSbSe_2$, $CuAsSe_2$, $CuAsS_2$, $AgSbSe_2$, $AgSbTe_2$, and Ag_3AsSe_3, have been synthesized by melting the stoichiometric amounts of the component elements in sealed silica tubes in nitrogen. All the compounds are semiconductors. The intrinsic energy gaps lie in the range 0.2 to 1.0 ev. The melting point of each compound is given.

WOODS, S. B. See abs. 92.

Studies of Tellurides and Selenides

103. AINSWORTH, L. Single Crystal Bismuth Telluride. Proc. Phys. Soc., vol. 69B, 1956, pp. 606-612.

Methods of preparation are described, and the results of thermoelectric and thermal- and electrical-conductivity measurements on single crystals of Bi_2Te_3 are presented. Segregation was prevented by pulling the crystal from the melt in a hydrogen atmosphere.

104. AIRAPETIANTS, S. V., EFIMOVA, B. A., STAVITSKAYA, T. S., STIL' BANS, L. S., AND SYSOEVA, L. M. [On the Mobility of Electrons and Holes in Solid Solutions Based on Lead and Bismuth Tellurides.] (Russian.) Zhur. Tekh. Fiz., vol. 27, No. 9, 1957, pp. 2009-2020; trans. in Sov. Phys. Tech. Phys., vol. 2, No. 9, 1958, pp. 2167-2169.

The mobilities were studied of the current carriers in the Bi_2Te_3-Bi_2Se_3, Bi_2Te_3-Sb_2Te_3, PbTe-PbSe, and PbTe-SnTe systems as a function of composition.

105. AMIRKHANOV, KH. I., BASHIROV, R. I., DAIBOV, A. Z., AND TSIDIL'KOVSKII, I. M. ["Drag" Effect in the Thermomagnetic Properties of Bismuth Selenide.] (Russian.) Doklady Akad. Nauk S. S. S. R., vol. 117, No. 5, 1957, pp. 781-784.

The Hall, thermoelectric, and Nernst-Ettinghausen effects have been measured from 100° to 700° K. on Bi_2Se_3.

106. AUSTIN, I. G., AND SHEARD, A. Some Optical Properties of Bi_2Te_3-Bi_2Se_3 Alloys. Jour. Electronics and Control, vol. 3, No. 2, 1957, pp. 236-237.

Measurements of the optical-energy gap as a function of composition showed a discontinuity at $Bi_2Te_{2.1}Se_{0.9}$, where the energy gap reaches a maximum value of 0.31 ev.

BASHIROV, R. I. See abs. 105.

107. BLACK, J., CONWELL, E. M., SEIGLE, L., AND SPENCER, C. W. Electrical and Optical Properties of Some $M_2^{V-B}N_3^{VI-B}$ Semiconductors. Jour. Phys. Chem. Solids, vol. 2, No. 3, 1957, pp. 240-251.

Several homologous compounds were synthesized and electrical and optical measurements made: As_2Se_3, As_2Te_3, Sb_2S_3, Sb_2Te_3, Bi_2S_3, Bi_2Se_3, and Bi_2Te_3.

108. BOLTAKS, B. I., KONOROV, P. P., AND MATVEEV, O. A. [Electrical Properties of Cadmium Telluride.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 2329-2335.

CdTe was prepared by heating the components in sealed quartz at 1,060°-1,080° C. for 2-3 hours. Measurements were made on the Seebeck coefficient, conductivity, and photoelectric effect as a function of composition for 0.1 to 1 percent Te, Au, Cu, and Cd from 25° to 500° C.

109. BOLTAKS, B. I., MATVEEV, O. A., AND SAVINOV, V. P. [Electrical Properties of Zinc Telluride.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 2097-2103.

Measurements were reported on ZnTe with stoichiometric composition, with 1 percent excess Te, and with 1 percent excess Se. The resistivity and thermal electromotive force were measured up to 600° C.

CONWELL, E. M. See abs. 107.

110. CULLITY, B. D., TELKES, M., AND NORTON, J. T. Electrical Resistivity and Thermoelectric Power of Antimony-Selenium Alloys. Trans. AIME, vol. 188, 1950, pp. 47-52.

SbSe alloys were shown to be unsuitable for use as power thermocouples.

DAIBOV, A. Z. See abs. 105.

111. DEVYATKOVA, E. D. [Study of the Thermal Conductivity of Lead Telluride.] (Russian.) Zhur. Tekh. Fiz., vol. 27, 1957, pp. 461-466; trans. in Sov. Phys. Tech. Phys., vol. 2, 1957, pp. 414-418.

With carrier concentrations from 10^{17} to 10^{18} per cc, 1/k varied linearly with absolute temperature up to 200° C. Then an addition to the thermal conductivity appeared, which was attributed to exiton thermal conductivity.

DOUGLAS, R. W. See abs. 116.

112. **DRABBLE, J. R., AND GOODMAN, C. H. L.** Chemical Bonding in Bismuth Telluride. Jour. Phys. Chem. Solids, vol. 5, 1958, pp. 142-144.

A model for the chemical bonding in Bi_2Te_3 is proposed which appears to dispose of some of the difficulties involved in earlier models. The new model is used to explain some of the properties of Bi_2Te_3 and its alloys with Bi_2Se_3.

113. **DRABBLE, J. R., GROVES, R. D., AND WOLFE, R.** Galvanomagnetic Effects in N-Type Bismuth Telluride. Proc. Phys. Soc., vol. 71B, 1958, pp. 430-443.

Hall-effect and resistivity measurements from 77° K. to room temperature are consistent with the predictions of the "many-valley" theory.

EFIMOVA, B. A. See abs. 104.

GOERING, H. C. See abs. 119.

114. **GOLDSMID, H. J.** Heat Conduction in Bismuth Telluride. Proc. Phys. Soc., vol. 72, 1958, pp. 17-26.

The calculated electronic component of the thermal conductivity was found to agree with the experimental results for p- and n-type Bi_2Te_3 but not for halogen-doped n-type material.

115. ___. Thermal Conductivity of Bismuth Telluride. Proc. Phys. Soc., vol. 69B, 1956, pp. 203-209.

Measurements were made in the temperature range 150° to 300° K. The electronic contribution to the thermal conductivity was greater for intrinsic specimens than for impurity specimens. This result is reasonable on the basis of a proposed theory, which concerns the transfer of ionization energy down a temperature gradient.

116. **GOLDSMID, H. J., AND DOUGLAS, R. W.** Use of Semiconductors in Thermoelectric Refrigeration. British Jour. Appl. Phys., vol. 5, 1954, pp. 386-390; erratum, p. 458.

Experiments were reported on the use of Bi_2Te_3 for thermoelectric refrigeration. A temperature difference of 37° was obtained. The theory of thermoelectric cooling was summarized.

117. **GOLDSMID, H. J., SHEARD, A. R., AND WRIGHT, D. A.** Performance of Bismuth Telluride Thermojunctions. British Jour. Appl. Phys., vol. 9, No. 9, 1958, pp. 369-370.

The figure of merit for n- and p-type Bi_2Te_3 between 150° and 300° K. has been shown to be greatest for a material with an electrical conductivity of 10^3 ohm^{-1} $cm.^{-1}$ with current flow parallel to the cleavage planes. Maximum cooling from 290° K. was 65° K., and about 1 percent efficiency was obtained for thermoelectric generation with 25° temperature difference.

GOODMAN, C. H. L. See abs. 112.

GORDIAKOVA, G. N. See abs. 127.

GROVES, R. D. See abs. 113.

118. **HAKEN, W.** Beitrag zur Kenntnis der thermoelektrischen Eigenshaften der Metallegierungen [Contribution to the Knowledge of Thermoelectric Properties of Metal Alloys]. (German.) Ann. Physik, Series 4, vol. 32, 1910, pp. 291-336.

The thermal electromotive force and electrical conductivity of cast and cooled alloys of Bi-Te, Bi-Sb, Sb-Ag, Te-Se, Te-Sn, and Te-Sb are presented as a function of composition.

119. **HARMAN, T. C., MILLER, S. E., AND GOERING, H. C.** Preparation and Electrical Properties of Bi_2Te_3. Phys. Rev., vol. 100, 1955, p. 1262.

The most satisfactory technique in preparing specimens for thermoelectric applications is to quench from above the melting point and then anneal for a long time just below the melting point. Zone melting of single crystals in a tellurium atmosphere is recommended.

120. **KOLOMOETS, N. V., STAVITSKAYA, T. S., AND STIL'BANS, L. S.** [Investigation of the Thermoelectric Properties of Lead Telluride and Lead Selenide.] (Russian.) Zhur. Tekh. Fiz., vol. 27, No. 1, 1957, pp. 73-81.

The thermal electromotive force, electrical conductivity, and carrier concentration were measured as a function of temperature for the whole range of solid solutions of Pb-Te and Pb-Se. Carrier mobility and effective cross section of scattering centers were deduced as a function of temperature and composition.

121. **KONOROV, P. P.** [Electrical Properties of Bismuth Chalcogens. II. Electrical Properties of Bismuth Selenide (Bi_2Se_3).] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 7, 1956, pp. 1394-1399; trans. Sov. Phys. Tech. Phys., vol. 1, No. 7, 1957, pp. 1365-1370.

This article contains measurements of electrical conductivity, Hall effect, and thermal electromotive force on polycrystalline and single crystal specimens of Bi_2Se_3 as a function of temperature.

122. ___. [Electrical Properties of Bismuth Chalcogens. III. Electrical Properties of Bismuth Telluride (Bi_2Te_3).] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 7, 1956, pp. 1400-1405; trans. Sov. Phys. Tech. Phys., vol. 1, No. 7, 1957, pp. 1371-1383.

This report includes measurements of electrical conductivity, Hall effect, and thermal electromotive force on polycrystalline and single crystal specimens of Bi_2Te_3 as a function of temperature.

___. See also abs. 108.

123. **KOVALCHIK, T. L., AND MASLAKOVETS, IU. P.** [Effect of Impurities on the Electrical Properties of Lead Telluride.] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 11, 1956, pp. 2417-2431; trans. Sov. Phys. Tech. Phys., vol. 1, No. 11, 1957, pp. 2337-2349.

Measurements were made on electrical conductivity, thermoelectric power, and carrier concentrations for PbTe specimens with different amounts of a wide variety of impurities.

MASLAKOVETS, IU. P. See abs. 123.

MATVEEV, O. A. See abs. 108, 109.

MILLER, S. E. See abs. 119.

NORTON, J. T. See abs. 110.

PINSKER, Z. G. See abs. 126.

124. **PUTLEY, E. H.** Thermoelectric and Galvanomagnetic Effects in Lead Selenide and Telluride. Proc. Phys. Soc., vol. 68B, 1955, pp. 35-42.

Single crystals were measured for the thermoelectric power and the Peltier, Nernst, Ettinghausen, and Righi-Leduc effects as a function of temperature to 1,100° K.

125. SATTERTHWAITE, S. B., AND URE, R. W., JR. Electrical and Thermal Properties of Bi_2Te_3. Phys. Rev., vol. 108, 1957, pp. 1164-1170.

The phase diagram in the region near Bi_2Te_3 was clarified, and the charge carrier density and thermoelectric power were measured as a function of atomic percent tellurium. The Hall coefficient and the thermal conductivity were measured for both n- and p-type specimens.

SAVINOV, V. P. *See* abs. 109.

126. SEMILETOV, S. A., AND PINSKER, Z. G. [Oxidation of Samples of Bi_2Se_3 and Bi_2Te_3 When Annealed in Air.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 2336-2338.

The lattice spacing of the compound was observed to decrease after anneals at 200° C. for times up to 30 minutes.

SEIGLE, L. *See* abs. 107.

SHEARD, A. R. *See* abs. 106, 117.

SHILLIDAY, P. F. *See* abs. 22.

127. SINANI, S. S., AND GORDIAKOVA, G. N. [Solid Solution Bi_2Te_3-Bi_2Se_3 as a Material for Thermoelements.] (Russian.) Zhur. Tekh. Fiz., vol. 26, No. 10, 1956, pp. 2398-2399; trans. in Sov. Phys. Tech. Phys., vol. 1, No. 10, 1957, pp. 2318-2319.

Results were given of measurements of electrical conductivity, thermoelectric power, and thermal conductivity for solutions of 80 atomic percent Bi_2Te_3 and 20 atomic percent Bi_2Se_3, with various admixtures of AgI, CuBr, Ag, or Cu. The alloy containing 0.05 weight-percent CuBr gives a figure of merit $\frac{\alpha^2\sigma}{\kappa}$ equal to 2.5×10^{-3} per degree. It has good mechanical properties and may be used as the negative element for thermal cooling.

SPENCER, C. W. *See* abs. 107.

STAVITSKAYA, T. S. *See* abs. 104, 120.

STIL'BANS, L. S. *See* abs. 104, 120, 130.

SYSOEVA, L. M. *See* abs. 104.

TELKES, M. *See* abs. 110.

TSIDIL'KOVSKII, I. M. *See* abs. 105.

URE, R. W., JR. *See* abs. 125.

128. VASENIN, F. I. [Thermoelectric Properties of Alloys in the Bismuth-Tellurium System.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 397-401.

Samples of alloys of Bi-Te were cast, pressed, and tempered and their thermoelectric powers and resistivities studied. The only compound found was Bi_2Te_3.

129. ___. [Thermoelectric Properties of the Antimony-Tellurium Alloy System.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 1190-1197.

The thermal electromotive force and electrical conductivity of Te-Sb_2Te_3 were studied. The melting point of Sb_2Te_3 is 612° C.; it oxidizes above 270° C.

130. **VLASOVA, R. M., AND STIL'BANS, L. S.** [Study of the Thermoelectric Properties of Bismuth Telluride.] (Russian.) Zhur. Tekh. Fiz., vol. 25, 1955, pp. 569-576.

Thermoelectric properties were measured as a function of temperature and composition up to 7 percent excess of Bi or Te from the correct stoichiometric composition.

WOLFE, R. See abs. 113.

131. **WRIGHT, D. A.** Thermoelectric Properties of Bismuth Telluride and Its Alloys. Nature, vol. 181, Mar. 22, 1958, p. 834.

This letter briefly mentions work in progress on alloys of Bi_2Te_3 with Bi_2Se_3, Sb_2Te_3, Bi_2S_3, and Sb_2Te_3 containing either selenium or sulfur additions at the General Electric Laboratories in Wembly, England.

___. See also abs. 117.

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